

EFFECTS OF MOUNTAIN PINE BEETLES AND TIMBER HARVESTING ON STAND ATTRIBUTES AND SNOW ON THE B.C. INTERIOR PLATEAU

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ABSTRACT

Considerable progress has been made in describing the effects of clearcut harvesting and reforestation on snow accumulation and melt relative to mature healthy forests. However, in the aftermath of the recent mountain pine beetle infestation in B.C., the effects of harvesting beetle-killed pine stands need to be compared with what would have happened if the killed stands had been allowed to develop naturally. This paper reports on a project in which snow accumulation and ablation were compared in recent clearcuts, partially recovered plantations, and natural pine stands at different stages of disturbance and recovery. SWE and ablation rates in treed plots were standardized by calculating ratios of SWE and ablation rates in treed plots to those in nearby clearcuts. SWE ratios were > 1 in only 3 of the 19 treed plots – a recently-defoliated stand and two plantations under 15 years old. Snow ablation ratios were > 1 only in a 15 year-old plantation. SWE ratios and ablation ratios in plantations and killed pine stands were analyzed as functions of time since disturbance. Results suggest that harvesting recently-killed pine stands could increase the rate of snowmelt for 15 to 25 years on the B.C. Interior Plateau.

INTRODUCTION

Evergreen conifers affect snow hydrology by reducing the amount of snow reaching the ground and the rates of ablation of snow that is stored on the ground. In a review of the literature, Winkler (2001) found that in 32 comparisons of snow in forests having various combinations of pine, fir, and spruce with unforested openings, snow accumulation averaged 26 percent less in the forest than in the clearcut (i.e., 35 percent more in openings than in the forest). Rates of melting, vaporization, and net ablation have also been found to be less in the forest. Winkler et al., 2005 observed ablation rates in a mature spruce-fir stand that averaged 40% of that in a clearcut (i.e. 2.5 times greater in the clearcut). Boon (2007, 2009) estimated ablation rates in three green pine stands to be from 51% to 73% of those in clearcuts. These differences decrease over time as plantations grow, resulting in snow accumulation and ablation rates that are intermediate between clearcuts and mature stands (e.g. Hudson, 2000 and Winkler et al., 2005). Winkler (2001) investigated relationships between forest stand parameters in two immature and one mature conifer stand and snow hydrology in the B.C. Interior. She found that stand average length of tree crowns explained 73% of the variability in average ratios of snow storage relative to nearby clearcuts and that square root of basal area explained 79% of the variability in average melt-rate ratios. Hudson (2000) explored similar relationships between stands properties and snow hydrology on the B.C. coast, concluding that snow accumulation and ablation in young managed stand are similar to those of mature stands when trees reach a height of 20 metres. This reduced effect of clearcutting on snow accumulation and ablation as trees regrow is encompassed in the concept of “hydrologic recovery” for forest planning purposes in British Columbia.

Mountain pine beetles (*Dendroctonus ponderosae*) have killed a large portion of canopy-forming pine trees over an area of approximately 14.5 million ha of the B.C. Interior (B.C. Ministry of Forests and Range, 2008). Previous work has shown that an intense beetle epidemic alone can increase spring runoff in a watershed having substantial snowfall (Bethlahmy, 1975). Beetle-killed stands in B.C. are being harvested at an accelerated rate as a matter of policy (BC Ministry of Forests and Range, 2004) but it is recognized that large areas will not be salvage logged. It is further recognized that those unlogged areas should be planned with hydrologic effects in mind (BC Ministry of Forests and Range, 2007). The combined hydrologic effects of retaining some dead stands and harvesting others will therefore be part of watershed management in much of B.C. for many years.

Paper presented Western Snow Conference 2009

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Figure 1. Study areas

Clearcuts on pine-leading sites are typically reforested with Lodgepole pine and recover relatively quickly. Beetle-killed pine stands are more complex than plantations, being composed of a combination of larger dead trees that deteriorate over time and a variable quantity of uneven-aged natural regeneration that will eventually produce net, stand-level recovery. At some time in the future, the structure and hydrologic state of stand that was mostly dead at time zero will be a function of the condition of deteriorating dead trees and the growing live trees, both of which change over time. Forest hydrologists have made considerable progress in quantifying the changing effects of plantations on snow accumulation and melt during hydrologic recovery but we do not know as much about the changing effects of complex natural stands on stand structure or snow hydrology. The purpose of this project is to document the effects of time since disturbance and stand structure on snow accumulation and snow ablation rates in beetle-killed stands compared with plantations in order to provide some insight to those interrelationships.

STUDY AREAS

Four study areas (Baker, Moffat, Rosita, and Vanderhoof in Figure 1) were established within an area spanning 250 km East-West and 180 km North-South on the B.C. Interior Plateau approximately centred on the area affected by the mountain pine beetle epidemic of the late 1990’s and early 2000’s (Natural Resources Canada, 2007). Three biogeoclimatic zones are represented – the Montane Spruce (Baker and Moffat study areas), the Sub-Boreal Pine-Spruce (Rosita), and the Sub-Boreal Spruce (Vanderhoof). As of 2005, natural stands in this sample ranged in age from 44 to 213 years while the managed stands had a maximum age of 33 years according to the B.C. Ministry of Forests and Range Vegetation Resources Inventory (VRI).

Each study area was selected based on the presence of a wide variety of natural and managed stands on low relief topography and in close proximity to each other. Elevations between study areas ranged from 880 to 1240 metres but within study areas, all plots were located within 4.6 kilometres distance and 24 metres elevation of each other. Slopes in all plots were 7 percent or less. Each study area contained 5 to 7 plots including a recent clearcut (trees < 1 m tall), one or two partially recovered managed stand, and between 2 and 4 natural pine stands with ages of 45 years or more. Table 1 lists plots names and stand age by study area.

METHODS

Plot Layout, Snow Survey Methods and Snow Parameters

Each research plot was laid out as a 6 by 6 grid on 10 metre centres within a 50 by 50 metre square. Each of the 36 points was marked on the ground with rebar and bamboo pole and provided the reference for snow surveys. A snow survey of a plot consisted of measuring snow depth 3 metres south of each stake and measuring density in a snow pit near the plot. To estimate density, a vertical 10 cm diameter core was collected in the side of the snow pit and was weighed in a plastic bag using a spring scale.

In this paper, the parameter used to compare snow storage between plots was SWE at the beginning of the sustained ablation period (the “active melt period” of Faria et al., 2000) because this is the amount available for rapid spring melt. If maximum SWE occurs before the start of the main ablation period the difference could be due to vaporization, which in young juvenile stands and clearcuts, is likely in the range of 1 mm/day on many winter days (Bernier, 1990; Bernier and Swanson, 1993). Therefore, SWE at the start of the main ablation period has a large effect on spring runoff generation than does absolute maximum SWE that might have occurred weeks earlier.

In the years 2006 and 2007, a single snow survey was done in each plot just before the main ablation period and the dates of snow disappearance were estimated from aerial surveys, thus providing a two-point SWE time series for each plot. The dates on which to do ground surveys were based on weekly reconnaissance snow surveys near each study area. The second point on the SWE curves in 2006 and 2007 were estimated by sequential aerial photography at approximately weekly intervals based on the assumption that SWE was rapidly approaching zero when half of the ground was snow-free. In 2008, SWE time series were estimated from six ground snow surveys of all plots.

Tree Surveys

In 2007, trees were surveyed in each snow plot within four circular sub-plots of 50 or 200 sq. m. each depending on the estimated number of stem per unit area. All stems taller than 1.3 m were categorized by species and crown condition. Because the crowns of many trees were in a state of transition due to recent mortality, crowns were categorized as green, green-red, red, red-grey, grey, and snag where “red” indicated that the needles were dead but still on the tree, “grey” indicated that all needles had dropped, and “snag” indicated that a dead tree had lost all of its small branches. In addition to the stem counts, a sample of up to 20 trees between 2 and 4 cm diameter at breast height (DBH) and up to 20 trees > 4 cm DBH were measured (the first 10 green trees and up to 10 red trees) in each circular plot. The heights and DBH’s were measured for trees with DBH greater than 2 cm. Those with DBH > 4 cm also had height to base of functional crown and crown diameter estimated. These data were used to estimate species composition, percentage of trees at different stages of deterioration, basal area, crown volume per unit area, and crown footprint. Defoliated pine trees were not measured. Killed stands were defined as those having more than 50% of stems dead in the 2007 tree surveys.

Canopy Radiation Transmittance

The portion of shortwave direct and diffuse solar radiation transmitted through canopies was estimated from hemispherical photos taken 1.1 m. above ground at each point in each plot in 2008. Above-canopy direct and diffuse radiation above the canopy ($K_{\downarrow 0}$) were determined from Gap Light Analyzer (Frazer et al., 1999) for cloud-free conditions in early April. Below-canopy radiation at the snow surface ($K_{\downarrow s}$) at each point was estimated as the sum of above-canopy radiation within each of 113 hemispherical sky segments times percent canopy gap within each corresponding segment of each hemispherical photo, determined using Scion Image for Windows (Scion Corporation <http://www.scioncorp.com/>). Plot average transmittance, T, was calculated as the average of $K_{\downarrow s} / K_{\downarrow 0}$ for each plot. The accuracy of this approach was confirmed by Hardy et al (2004) and methods are described in more detail in Teti (2008).

RESULTS

Variability of SWE’s and Ablation Rates

Table 1 summarizes selected stand structure parameters, SWE’s and ablation rates in 2006 through 2008. In most years and most plots, the main ablation period started in mid- to late-March and ended in mid-to late-April. SWE’s varied considerably between plots, between study areas, and between years, ranging from 43 mm in a mature grey-attacked stand in 2006 in the Rosita study area to 311 mm in the clearcut at the Baker study area in 2007. Average ablation rates ranged from 1.2 mm/day in the 30 year-old plantation at the Moffat study area in 2008 to 7.0 mm/day in the clearcut at the Rosita study area in 2008. In order to focus attention on the effects of *plot* on SWE and ablation rate rather than the effects of *study area* or *year*, each year’s SWE and ablation rate in each plot were divided by corresponding values in the nearby clearcut to get a “SWE ratio” and “ablation ratio”, which were averaged over the three years.

Overview of SWE Ratios and Ablation Ratios in Treed Plots

Average SWE ratios ranged from 54% to 130% and average ablation ratios ranged from 46% to 111% but most of this variability occurred within the Moffat study area. In the Baker study area, average SWE ratios in treed plots had a relatively small range (54 to 82%). In the Vanderhoof study area, treed plots had relatively small ranges in both parameters (SWE ratios from 78 to 91% and ablation ratios from 55 to 70%). At Rosita, SWE ratios in the five treed plots averaged 76 to 111% while ablation ratios ranged from only 60 to 78%. The Moffat study area was unusual in that average SWE’s of three of the treed plots were greater than that in the clearcut. Plot MO1, a mature pine stand that was attacked by beetles in 2005 and lost most of its needles before April 2007, had an average of 30% higher SWE but 19% lower ablation rate than the Moffat clearcut. Plot MRC1, a 10 year-old plantation, was the only treed plot that had a higher average ablation rate than the nearby clearcut.

Table 1. List of plots, stand characteristics, and snow data for the Baker (B), Moffat (M), Rosita (R), and Vanderhoof (V) study areas.

									2006		2007		2008		Average SWE ratio (11)	Average ablation ratio (12)
Plot	Age (1)	Age (2)	Height (3)	SPH (4)	Dead (5)	BA, R-G (6)	Gap (7)	T (8)	SWE (9)	Abl rate (10)	SWE (9)	Abl rate (10)	SWE (9)	Abl rate (10)		
BCC	2	2	0	0	NA	0	92%	89%	152	5.6	311	5.7	179	6.7	1.00	1.00
BOD1	216	3	15	1312	69%	14.2	61%	30%	97	2.9	194	3.5	122	4.6	0.65	0.61
BOD3	211	3	15	550	75%	6.2	74%	43%	108	4.0	172	4.0	99	4.6	0.60	0.70
BON	126	126	14	4103	47%	30.8	41%	23%	79	2.1	169	3.1	99	3.5	0.54	0.48
BRC1	8	8	4	1312	0%	4.5	96%	73%	123	4.6	214	5.0	110	5.1	0.70	0.82
BRC2	33	33	10	1025	40%	14.1	57%	39%	103	3.0	174	3.2	108	4.8	0.61	0.61
BYN	126	2	14	3853	77%	13.4	61%	31%	126	4.7	191	3.5	131	5.2	0.72	0.74
MCC	2	2	0	0	NA	0.0	100%	100%	90	4.1	101	5.6	136	5.9	1.00	1.00
MO1	128	3	17	2237	79%	8.9	61%	39%	83	3.8	182	6.5	160	2.0	1.30	0.81
MO3	128	3	21	1774	73%	12.4	57%	41%	79	3.6	127	3.6	139	4.7	1.05	0.77
MRC1	10	10	0	0	NA	0.2	100%	94%	107	7.1	118	5.4	154	3.6	1.16	1.11
MRC2	29	29	10	1537	36%	18.7	48%	26%	53	2.4	116	3.3	118	1.2	0.87	0.46
RCC	2	2	0.0	0	NA	0.0	100%	93%	55	6.9	147	4.0	117	7.0	1.00	1.00
ROD1	199	25	8.0	2099	13%	18.7	69%	43%	57	3.8	125	2.8	104	3.8	0.92	0.60
ROD2	213	25	5.0	1687	4%	11.2	77%	56%	66	4.4	134	3.6	90	2.9	0.96	0.65
RON	213	2	15.5	1425	70%	17.2	65%	41%	43	5.4	98	2.6	96	3.7	0.76	0.65
RRC1	12	12	3.3	325	4%	2.1	96%	74%	81	5.4	150	4.0	100	3.7	1.11	0.78
RYN2	44	44	6.2	8847	3%	26.4	60%	27%	62	4.1	112	3.0	85	4.1	0.87	0.65
VCC	2	2	0.0	0	NA	0.0	100%	100%	103	7.9	272	6.6	158	5.7	1.00	1.00
VOD1	135	135	7.3	1387	47%	5.0	56%	37%	67	2.3	209	4.5	149	4.7	0.79	0.60
VOD2	135	5	11.8	1687	84%	5.0	67%	31%	104	3.6	214	5.2	150	4.9	0.91	0.70
VRC1	13	13	4.6	1500	2%	5.8	81%	56%	88	4.4	211	6.2	137	3.4	0.83	0.70
VYN	75	75	10.0	7648	23%	28.7	42%	25%	90	3.1	187	3.2	123	4.3	0.78	0.55

Table 1 Notes:

1. Stand age from the Vegetation Resource Inventory as of 2005 (years)
2. Years since stand replacement by logging or beetle-kill if > 50% dead
3. Average height of stems that were green to red and had DBH > 4cm (metres).
4. Density of all stems, green to snag, > 4 cm DBH (stems per ha)
5. Number of standing dead stems > 4 cm DBH / Total stems (dimensionless). NA = no stems > 4cm DBH
6. Basal area of green to red stems having DBH > 4cm, (m²/ha)
7. Plot average gap fraction within 30 degree zenith angle (dimensionless)
8. Plot average portion of radiation transmitted in early April under clear skies (dimensionless).
9. SWE at the start of the main ablation period (mm)
10. Maximum average ablation rate between sequential surveys (mm/day)
11. 3-year average ratio of SWE in plot to SWE in clearcut
12. 3-year average ratio of ablation rate in plot to ablation rate in clearcut

SWE Ratios and Stand Structure

Average SWE ratios were regressed against plot average values of crown volume per unit area, square root of basal area, and canopy gap in a 30 degree zenith angle. When all plots were analyzed together, no statistically significant relations were found but there were positive correlations between SWE ratio and canopy gap in three study areas when study areas were analyzed separately as shown in Figure 2. Similar results were found in regressions between SWE ratios and the square root of basal area. The r² values between SWE ratios and canopy gap at the Baker, Moffat, Rosita, and Vanderhoof study areas were 0.49, 0.04, 0.69, 0.70, while those between SWE ratios and square root of basal area were 0.75, 0.05, 0.49, and 0.63.

Ablation Ratios and Stand Structure

Average ablation ratios were regressed against crown volume per unit area, basal area, and solar radiation transmittance. There were good correlations between ablation ratios and stand structure parameters when all study areas were grouped together. Ablation ratios in all plots were highly-correlated with both radiation transmittance ($r^2 = 0.8040$) and the square root of basal area ($r^2 = 0.7875$) as shown in Figure 3. Since the data were standardized using SWE's and ablation rates in clearcuts, the data points for the clearcuts could be regarded as biased. With the clearcut data removed, the r^2 values for average ablation ratios versus transmittance and the square root of basal area were 0.6362 and 0.6038 respectively. These results suggest that radiation transmittance and the square root of basal area contain similar information about stand structure, even though only the basal area of green to red trees was used in the basal area calculation.

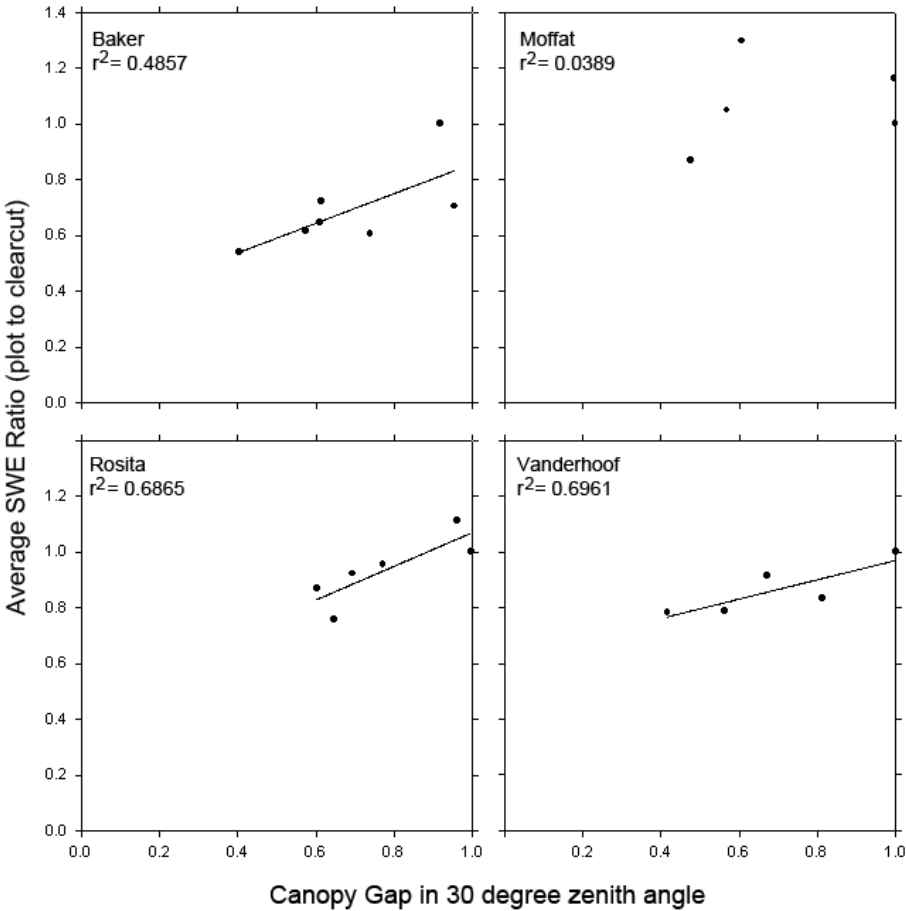


Figure 2. Average SWE ratios versus canopy gap in each study area

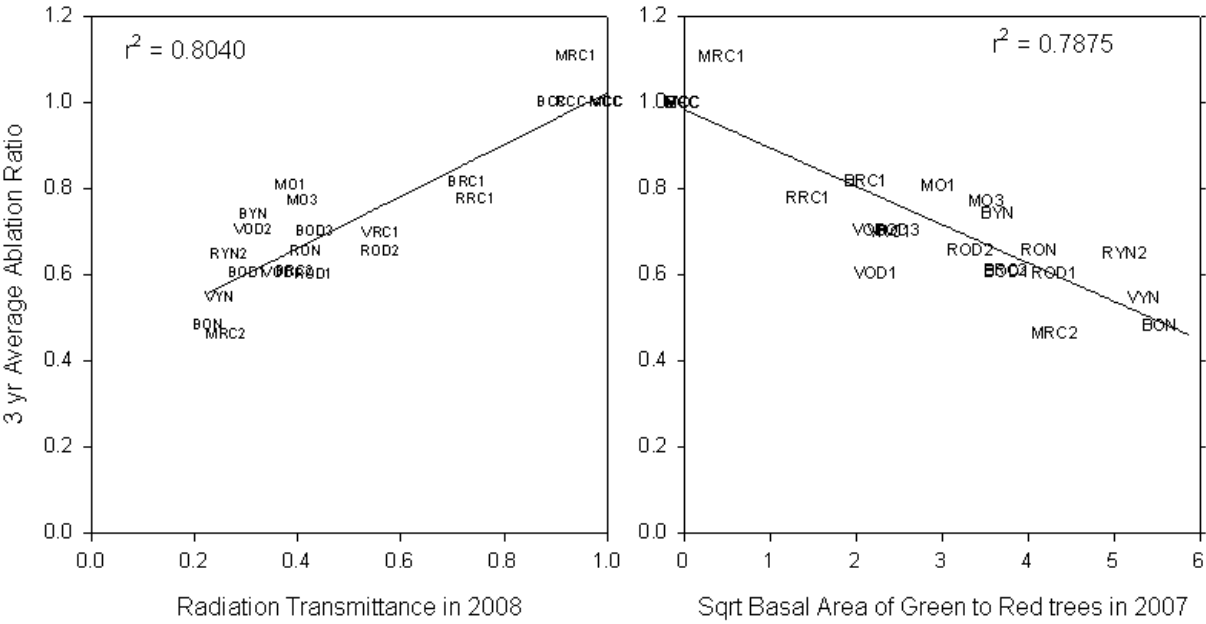


Figure 3. Average ablation ratios versus plot average radiation transmittance and square root of basal area.

Effects of Logging Dead Pine stands on Snow Hydrology

The relative effects of a plantation on SWE and ablation rate compared with a killed stand can be expressed as

$$\frac{SWE_{plantation,tc}}{SWE_{killed\ stand,tk}}$$

and

$$\frac{Ablation\ rate_{plantation,tc}}{Ablation\ rate_{killed\ stand,tk}}$$

where tc = time since clearcutting and tk = time since the stand was killed.

The most powerful way to detect this difference would be to measure SWE’s and ablation rates in adjacent plantations and killed stands, with replication, and over a number of years. However, an alternative is to estimate SWE ratios and ablation ratios as functions of time for a sample of (killed stand) / (clearcut) pairs and a sample of (plantation) / (clearcut) pairs. Comparisons can then be made between regression lines rather than individual data points. By calculating standardized SWE ratios and ablation ratios we can combine data from plots in different locations. The killed stands and plantations do not have to be near each other as long as each one is near a clearcut. This study provides such a set of data with 6 plantation / clearcut pairs and 9 killed stand / plantation pairs.

The ages of beetle-killed stands in column 2 of Table 1 from the B.C.’s VRI are the estimated ages before beetle-kill. For each of the 9 plots which had been beetle-killed, the number of years since mortality was estimated from forest disturbance data fields in the VRI, from personal observation, and from beetle spread maps (<http://cfs.nrcan.gc.ca/subsite/mpb/historical-historique>). Figures 4a and 4b show SWE ratios and ablation ratios versus time for killed stands and plantations. Linear regression models and 95% confidence limits on regressions are shown. Because SWE ratios were correlated with gap fraction in three of the four study areas, and ablation ratios were correlated with solar radiation transmittance in all study areas, those stand parameters were also plotted versus time and regression lines calculated. Regressions and 95% confidence limits are shown in Figures 4c and 4d.

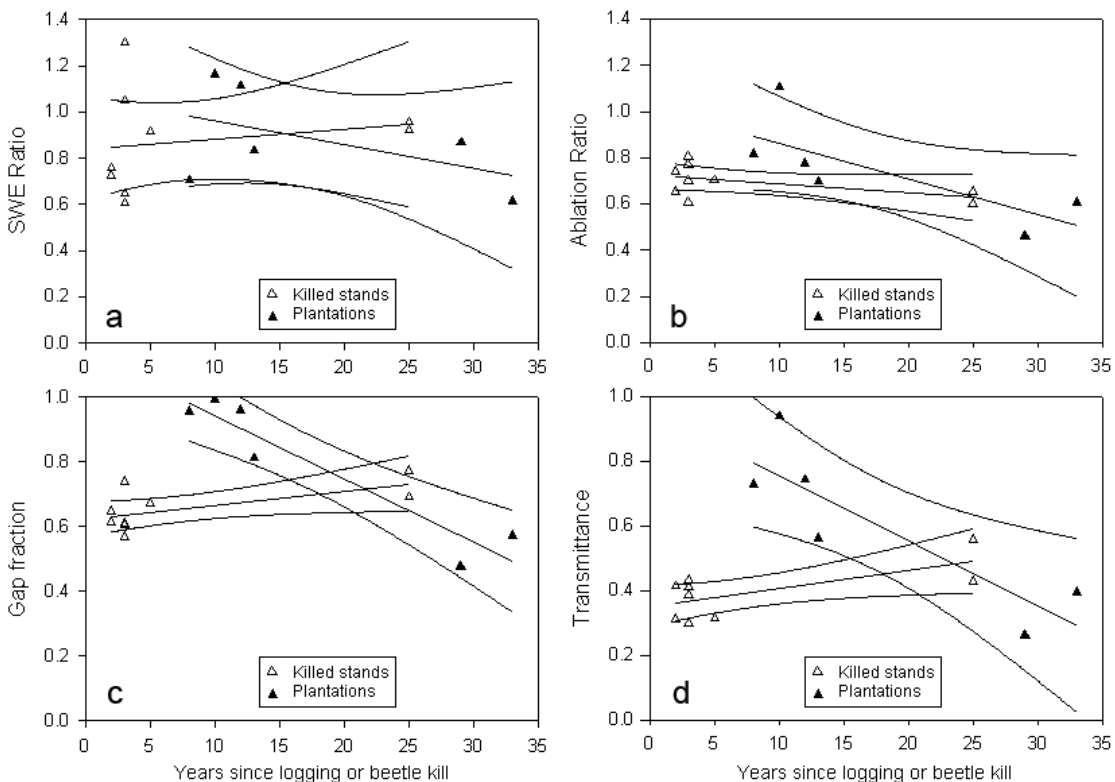


Figure 4. Average SWE ratios (a), ablation ratios (b), gap fractions (c), and solar radiation transmittances (d) versus time since logging in plantations and time since mortality in beetle-killed stands. Regression lines and 95% confidence intervals on regressions are shown.

DISCUSSION

Stand Structure Parameters Related to SWE and Ablation Rate

As discussed in the Introduction, previous studies have shown that stand structure parameters can explain significant portions of the variability in snow accumulation and ablation rates when the data are standardized to clearcuts. Winkler (2001) found that SWE ratios and ablation ratios were correlated with crown length, square root of crown volume, and crown closure. Her ablation ratios were also correlated with the square root of basal area. However, that was prior to the current beetle epidemic. Given the complexity of pine stands containing large numbers of deteriorating trees, many of those stand descriptors are now problematic because the perimeters and internal characteristics of dead tree crowns are difficult to define. However, Winkler's (2001) results also show that crown length, crown volume, crown area, and basal area contain largely redundant information. Of the field parameters, DBH (from which basal area is derived) is one of the most attractive for use in attacked stands as long as crown condition is also noted. Optically measured parameters are also attractive in the aftermath of the beetle epidemic because they do not require any judgements about crown condition.

Canopy gap in a 30-degree zenith angle was chosen as a predictor of SWE ratios because previous results (Teti, 2003) indicated that it was an effective and rational parameter for explaining plot average differences in snow storage. An alternative is Leaf Area Index but LAI is highly-correlated with optically measured canopy gap (or canopy density, e.g. Pomeroy et al., 2002) and is generally estimated by optical methods anyway. Radiation transmittance in early April under clear skies was chosen as a predictor of ablation ratios because 1) net radiation is the major source of snowmelt energy in openings, conifer stands, and defoliated stands (Spittlehouse and Winkler, 2004; Thyer et al, 2004; Hardy et al., 1998); 2) the highest incoming radiation occurs on clear days; and 3) early April is the approximate mid-point of the main ablation period in these study areas. The selection of tree measurement parameters for this study presented more of a challenge. When the tree surveys were being planned, it was speculated that the crowns of defoliated trees would not affect SWE or ablation rates so defoliated trees were counted but not measured. Thus in this study, the effects of defoliated pine trees are represented in the canopy gap and radiation measurements but not in the basal area measurements.

SWE Ratios Versus Stand Structure

In contrast with other studies (Winkler, 2001; Talbot and Plamondon, 2002), no stand structure parameter was found that could consistently explain stand average SWE ratio across all study areas. Neither canopy gap nor the square root of basal could explain most of the variability in stand average SWE ratios when study areas were combined. This could be due to a confounding effect of canopy when different winter weather between study areas causes different ablation episodes during the net accumulation season. It has been shown that the percentage of intercepted snow (Schmid and Gluns, 1991) and its fate of (i.e. unloading, melt, or vaporization, Pomeroy, et al., 1998) vary with the weather. The fate of snow stored on the forest floor is also subject to variable ablation processes during the net accumulation season if weather conditions are conducive. For example, low canopy density tends to allow more snow to accumulate during snowfall but low canopy density could also result in more ground-level ablation between snowfalls, depending on wind speed, air temperature, humidity, and solar radiation (e.g. Bernier, 1990; Bernier and Swanson, 1993). Differences in winter weather between study areas could therefore be sufficient to explain inconsistent correlations between late winter SWE and canopy structure parameters. The same argument would apply to different correlations in one study area between years. The poor correlation between stand structure and net accumulation in the Moffat plots suggests that the Moffat study area might be a good location to study complex wintertime accumulation and ablation processes.

Ablation Ratios Versus Stand Structure

Even with clearcut SWE ratios removed from Figure 3a, radiation transmittance in treed plots explained 64 percent of the variance in average ablation ratios across all study areas. The square root of basal area was similarly effective, suggesting that the processes by which canopy affects the main snow ablation event of the year are simpler than those by which it affects net snow accumulation. As a result, both radiation transmittance and basal area appear to be good indices of relative snow ablation rates in pine-leading treed stands having a wide variety of disturbance histories and structures on the B.C. Interior Plateau. The better correlation between ablation ratios and stand structure than SWE ratios and stand structure could be that the former reflects a more consistent role of the canopy in reducing solar radiation whereas the latter reflects an alternating positive and negative effect of the canopy on net accumulation in winter. During the net accumulation season, more gaps can allow more accumulation during snowstorms but they can also allow more ablation when the weather is conducive to vaporization and melt.

Stand Structure and Snow Parameters Versus Time Since Disturbance

Figures 4c and 4d suggest that in these study areas, gap fraction and radiation transmittance in plantations and killed stands follow similar patterns of change versus time since disturbance. The regressions suggest that the values of those parameters in plantations cross the values in killed stands at 20 to 25 years. No such statements can be made about SWE ratios in plantations versus those in killed stands due to the high variability of SWE ratios (Figure 4a). This could be because stand structure affects net SWE through a combination of positive and negative effects depending on winter weather as discussed above.

The ability to discriminate ablation ratios versus time in plantations from those in killed stands is a little better as shown in Figure 4b. If one is willing to accept an alpha error probability greater than 5 percent, the regression lines (and the fact that ablation ratios in clearcuts equal 1 by definition) indicate that plantations have higher SWE ratios than killed stands for approximately 15 years and that they have lower SWE ratios than killed stands after 25 years. However, the small sample size and absence of plots in killed stands between the age of 5 and 25 years since attack means that the linear regression for killed stands in Figure 4b is very preliminary. The time required for dead stems to fall down and for killed stands to be regenerated is expected to be variable. It should be noted that Figures 4a, b, c, and d show data for plantations and killed stands with the same date of disturbance. If salvage logging is done x years after a stand is killed, then the data for plantations would be shifted x years to the left in Figure 4.

CONCLUSIONS

Average snow ablation ratios changed consistently with solar radiation transmittance (and basal area) across a wide variety of Lodgepole pine stands and a large geographic area. No similarly universal relations were found between SWE at the beginning of the main ablation season and stand structure parameters. It is hypothesized that was due to interactions between canopy structure and different wintertime ablation conditions between study areas. This implies opportunities for more research on wintertime processes that affect net accumulation, especially in the Moffat study area.

There were systematic temporal changes in the structure and snow hydrology of pine plantations after logging, and in killed stands after canopy mortality. Clearcuts and plantations are expected to produce faster snowmelt than severely-attacked pine stands for a period of 15 years after logging. However, after 25 or 30 years, most plantations should have slower snowmelt than killed pine stands that have developed naturally for that amount of time. Although the rate of deterioration and recovery of killed stands is subject to more variability than is suggested by this small sample, the results should help watershed managers make decisions which involve different costs and benefits over short and medium time periods.

The results point to a course by which future work could reduce uncertainty. One of the higher priorities is to measure SWE and ablation rates in killed stands approximately 10 to 20 years after disturbance and in nearby clearcuts. This would provide an improved sample of SWE and ablation ratios in killed stands and the results could be merged with those reported herein.

ACKNOWLEDGEMENTS

Funding for projects MPBI #8.39 and #7.33 was provided by Natural Resources Canada's Mountain Pine Beetle Initiative. Theo Mlynowski and Jessica Craig were unfazed by field conditions and repetitive tasks while assisting with data collection and analysis. The reliable contracting team of Scott and Janet Zimonick carried out snow surveys and tree surveys. West Fraser Mills Ltd., Tolko Industries, B.C. Timber Sales, and Canfor Corporation supported the project by helping protect plots and by maintaining roads in winter.

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